生态安全格局视角下城市边缘废弃矿山生态修复路径研究——以天津市蓟州区为例

Research on Ecological Restoration Path of Abandoned Mines in Urban Fringe Areas from the Perspective of Ecological Security Pattern — With the Example of Jizhou District, Tianjin

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摘要：针对城市边缘地区废弃矿山造成的区域和城市生态安全威胁，从区域生态安全格局出发，研究废弃矿山生态修复问题。运用专家综合评价法和层次分析法，构建了由水文、地质、生物、文化4个子系统下17个影响因子构成的城市边缘废弃矿山区域生态安全格局评价模型，基于模型提出了重构废弃矿山区域生态安全格局、引导国土空间布局优化的方法，并以天津市蓟州区为例开展了生态修复技术的实践探索。研究成果可以应用于周边类似地区废弃矿山生态修复中，进而推进海河流域源头地区生态环境的综合治理和京津冀地区的生态协同发展。
关键词：区域生态安全格局；流域源头治理；废弃矿山；生态修复
Abstract: Considering the regional and urban ecological security threats caused by abandoned mines in urban fringe areas, the problem of ecological restoration of abandoned mines is studied on the basis of regional ecological security pattern. By means of comprehensive evaluation method and analytic hierarchy process, an evaluation model of regional ecological security pattern of post-mining areas in urban fringe is designed, which is composed of 17 indicators allocated in 4 subsystems of hydrology, geology, biology and culture. Based on the model, methods to reconstruct the regional ecological security pattern and to instruct the optimization of the territorial spatial pattern in post-mining areas are proposed. Then, technical points on ecological restoration of abandon mines are explored, taking the example of Jizhou district in Tianjin. The research result can be applied to the ecological restoration of abandoned mines in the surrounding similar areas and to promote the comprehensive management of eco-environment in the Beijing--Hebei region.
Key words: regional ecological security pattern; headstream area management of river basins; abandoned mines; ecological restoration

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1. 研究背景

快速城市化时期，城市建设与经济发展过度依赖资源的开发与利用。随着发展方式的转变，各地矿山相继关停，截至 2016 年，全国矿山地质环境重点治理区 524 个，采矿累计损坏土地超过 375 万公顷[1]。大量废弃矿山不仅危害了周边的生态环境及居民的生产生活安全，也影响了所在区域的生态安全格局。

自党的十八大提出“生态文明建设”战略部署以来，区域生态协同治理受到各级政府的高度重视。流域内的山水林田湖草是一个生命共同体[2]，以流域为单元开展生态环境修复，重构生态安全格局是推进区域生态协同的重要手段。以废弃矿山生态修复为先导的山区环境综合治理是流域源头生态单元重建的关键。

当前，对废弃矿山生态修复的研究多局限于矿山自身的地质安全、植被恢复、土地复垦与再利用等问题，忽略了对其周边区域的影响。将区域生态安全格局理论引入废弃矿山生态修复研究，从区域视角统筹水文、地质、生物、文化等多要素系统治理，对实现矿区生态和土地可持续利用具有重要意义。

2. 生态安全格局理论与废弃矿山生态修复

2.1 生态安全格局理论的演化与应用

20 世纪中期，麦克哈格的“设计结合自然”通过地图叠加的手段实现了用地适宜性的综合评价方法，成为生态安全格局理论的雏形[3]。20 世纪末期，在生态规划理论与景观生态学理论的基础上衍生出景观城市主义理论，倡导将生态景观作为城市发展的基本格局[4]。21 世纪初期，俞孔坚基于景观生态学理论提出了支持自然生态系统，为城市和居民提供生态服务，维护生态系统完整性、稳定性的关键性格局——生态安全格局理论[5]。

生态安全格局理论早期主要应用于自然保护区等生态敏感地区的分析研究，随后逐渐被引入城市建设的用地适宜性评价、城市发展边界划定和生态系统规划等领域。矿山生态修复研究中对该理论应用较少，可检索到的文献中仅有曾晖、张宏杰等（2010），魏聪礼、张建军等（2017）从区域生态安全格局构建的角度对武安市矿区生态恢复的路径和方法进行了研究[6][7]。

2.2 废弃矿山生态修复的实践与不足

国际上，废弃矿山生态修复起步较早。20 世纪 60 年代起，各国开展了大量矿山生态修复与工程性改造。至 20 世纪末期，德国等欧洲国家，将工矿用地生态修复与城市大事件相结合，带动了区域文化复兴。21 世纪以来，在英国伊甸园计划等项目中，新技术、新材料逐步被应用到矿山修复中，实现了自然与人工环境的有机共生。在我国，徐州、平顶山等早期矿山生态修复实践以单纯土地复垦为主。2011 年以来，在上海辰山、湖北黄石等矿山公园建设中，初步实现了矿区生态修复与景观重建的统一。

目前，废弃矿山生态修复主要存在两方面问题。宏观上，传统的治理模式关注于矿区本身的景观与生态效果，没有把矿区生态修复与区域的水文环境、生态格局重塑相融合，无法实现区域生态环境的持续改善。微观上，大部分治理工程只考虑了消除地质灾害隐患和简单的绿化美化，治理效果具有局限性，通常无法满足远期综合利用的需要。

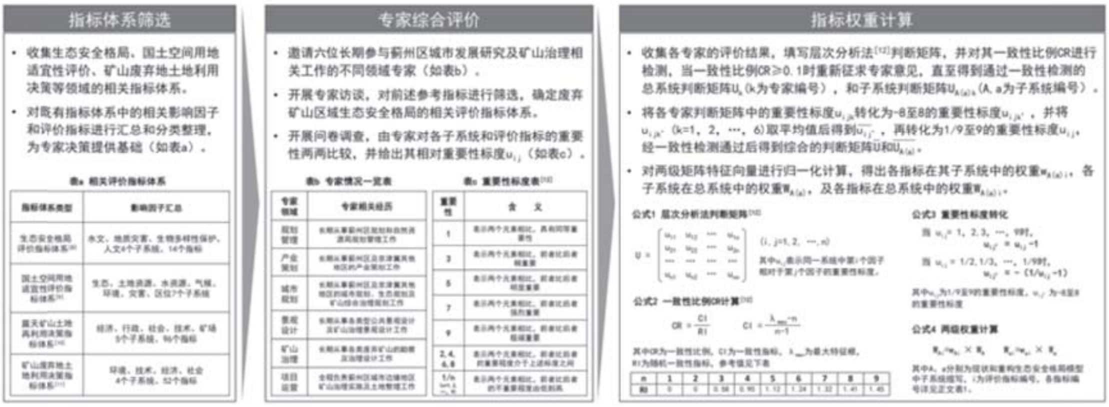


图1 废弃矿山区域生态安全格局评价模型的建构路径

Figure 1 Path Diagram of Evaluation Model Design for Regional Ecological Security Pattern in Post-mining Areas

2.3 生态安全格局视角下废弃矿山生态修复的要点

将生态安全格局理论和生态敏感性分析方法引入废弃矿山生态修复中，可以改变原有孤立的个体修复模式，实现矿区与区域生态系统全要素的修复与重建，其要点体现在以下两个方面：

一是宏观的辐射性。在确定各矿区土地再利用模式时，综合考虑流域尺度的生态修复与工矿用地转型要求，系统安排开放空间与建设用地，重构生态安全格局，优化国土空间布局。

二是微观的综合性。在确定各矿区生态修复方案时，统筹考虑水文、地质、生物、文化等各系统要素的修复要求及其协同关系，形成集工程化、生态化、景观化于一体的生态修复技术。

3. 生态安全格局视角下废弃矿山生态修复的目标

矿山开采不同程度地破坏了区域水文、地质、生物等自然子系统的稳定，造成了水系割裂、雨洪调蓄能力降低，地质灾害隐患严重、景观风貌差，水土流失、植物生境被破坏等问题。同时，工业化开采也遗留了大量工矿用地和文化遗存，为区域复兴提供了宝贵的文化资源。

因此，生态安全格局视角下废弃矿山生态修复的目标是：修复水文系统，增强雨洪调蓄能力；重塑地形地貌，维护地质生态安全；改善土壤环境，恢复多层次植物生境；串联游憩网络，活化矿业文化资源；最终实现生态的系统性修复与区域的可持续发展。

4. 生态安全格局视角下废弃矿山生态修复的方法

研究以天津市蓟州区为例，邀请了六位长期参与在地相关工作的专家，通过访谈和问卷调查等方式，对华北平原、京津冀地区的特殊地理环境中，废弃矿山区域的生态安全格局构成及其评价模型开展研究。首先，结合既往生态安全格局、国土空间用地适宜性评价研究中提出的相关影响因子[8][9]，综合考虑废弃矿山特殊的环境特征及修复目标[10][11]，提出了由水文、地质、生物等自然生态子系统和文化人文生态子系统构成的废弃矿山区域生态安全格局，并确定了各子系统包含的若干自然和人工环境影响要素及其评价标准，分别用于表征废弃矿山区域的现状及重构生态安全格局。在此基础上，运用专家综合评价法和层次分析法[12]，确定各子系统及各因子的权重，通过如图1所示路径，构建废弃矿山区域生态安全格局评价模型。

水文安全格局是维护区域生态安全的基础。自然水文环境包括湖泊、河流等常年覆盖的

地表水体及汇水廊道、湿地等季节性水域；人工水文环境包括排洪沟道、雨污水管网等灰色基础设施，及矿山治理中修复的汇水廊道、人工湿地等绿色基础设施。研究选取地表水体、季节性水域、灰色基础设施三个指标作为现状评价指标，绿色基础设施作为重构评价指标，共同构成区域水文安全格局。

地质安全格局是废弃矿山区域修复的重点。自然地质环境包括坡度、高程等地形地貌特征，和地震灾害区及断裂带、地质灾害易发区等地质安全特征；人工地质环境包括矿山治理后遗留的地质灾害危险区及缓冲区，以及设计特殊地形区域。研究选取自然地质环境的四个指标作为现状评价指标，人工地质环境的两个指标作为重构评价指标，共同构成区域地质安全格局。

生物安全格局是区域生态持续稳定的保障。自然生物环境包括植物群落和动物群落，其中动物群落的空间分布情况可以通过植被的分布、种类和生长状况间接分析；人工生物环境包括技术角度划定的治理后适宜种植区域，及政策角度确定的基本农田及生态储备林等区域。研究选取归一化植被指数（NDVI）和绿地类型作为现状评价指标，人工生物环境的两个指标作为重构评价指标，共同构成区域生物安全格局。

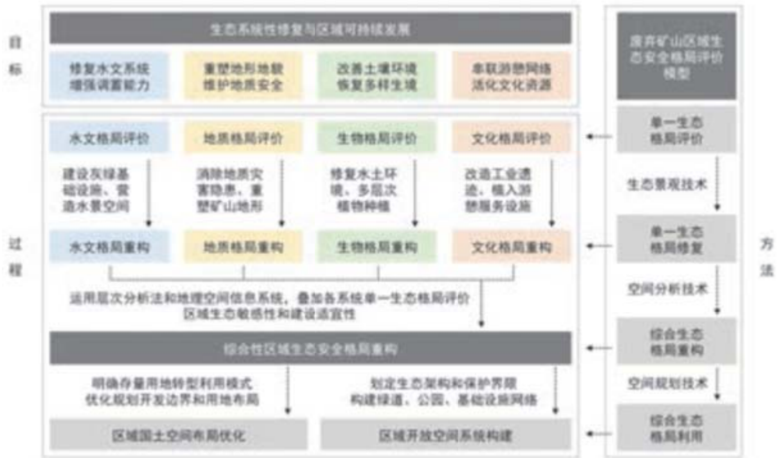


图2 废弃矿山生态修复的目标、过程和方法

Figure 2 Objective, Process and Method of Ecological Restoration in Abandoned Mines

表1 废弃矿山区域生态安全格局评价模型

Table 1 Evaluation Model of Regional Ecological Security Pattern in Post-mining Areas

分格局	分格局权重	评价指标	评价标准					现状评价模型		重构评价模型	
			1	2	3	4	5	子系统权重	总权重	子系统权重	总权重
水文（H）	0.287908	地表水（河道、坑塘沟渠）(H1)	一级河道60m缓冲范围及水库一级保护区	二级河道30m缓冲范围、水库二级保护区	等级河道200m缓冲范围、坑塘沟渠	水库准保护区	其他区域	0.539615	0.155359	0.359172	0.103409
		季节性水域（H2）	——	汇水廊道25m宽度	——	汇水廊道50m宽度	其他区域	0.163424	0.047051	0.123302	0.035500
		排水管网（H3）	——	截洪沟50m宽度	排水管网10m宽度	——	其他区域	0.296961	0.085498	0.192978	0.055560
		设计汇水廊道、水域（h1）	——	设计汇水廊道25m宽度	设计汇水区域	——	其他区域	——	——	0.324549	0.093440
地质（G）	0.476452	高程（G1）	>500m	150-500m	80-150m	30-80m	<30m	0.088335	0.042087	0.045159	0.021516
		坡度（G2）	>25°	15-25°	8-15°	5-8°	<5°	0.239458	0.114090	0.095598	0.045548
		地震灾害区、断裂带（G3）	断裂带	——	中等震灾区及断裂带200m缓冲范围	——	轻微震灾区	0.239458	0.114090	0.095598	0.045548
		地质灾害易发区（G4）	易发区	——	中等易发区	——	其他区域	0.432749	0.206184	0.191197	0.091096
		设计地质灾害缓冲区（g1）	地质灾害缓冲区	——	地质灾害缓冲区100m范围	——	其他区域	——	——	0.353582	0.168465
		设计特殊地形区（深坑、台地、陡坡）(g2)	设计陡坡及深坑	设计台地	设计特殊地形50m缓冲范围	——	其他区域	——	——	0.218866	0.104279
生物（B）	0.154689	植被覆盖率（NDVI）(B1)	>0.45	——	0.25-0.45	——	<0.25	0.666667	0.103126	0.470361	0.072760
		绿地类型（B2）	有林地、灌木林、草地等生态绿地	园地、水田、旱田等农业绿地	城市绿地	——	其他区域	0.333333	0.051563	0.279679	0.043263
		基本农田保护区及生态储备林（b1）	——	基本农田范围内	生态储备林范围内	——	其他区域	——	——	0.114178	0.017662
		设计适宜种植区域（b2）	——	设计复绿创面区域	设计湿地植被区域	设计适宜种植平台区域	其他区域	——	——	0.135782	0.021004
文化（C）	0.080951	文化遗产（C1）	特色工业文化遗存	特殊工业遗存及线路周边50m范围内	矿山特殊地形区域范围内及地质文化保护范围内	特色乡土文化遗产区域	其他区域	1.000000	0.080951	0.500000	0.040476
		游憩线路（c1）	——	主要游憩线路20m宽度	主要游憩线路两侧25m缓冲带、次要游憩线路及城市绿道20m宽度	次要游憩线路及城市绿道两侧25m缓冲带	其他区域	——	——	0.250000	0.020238
		文化及服务节点（c2）	——	设计文化设施及主要服务节点周围50m	设计服务节点周围25m	——	其他区域	——	——	0.250000	0.020238

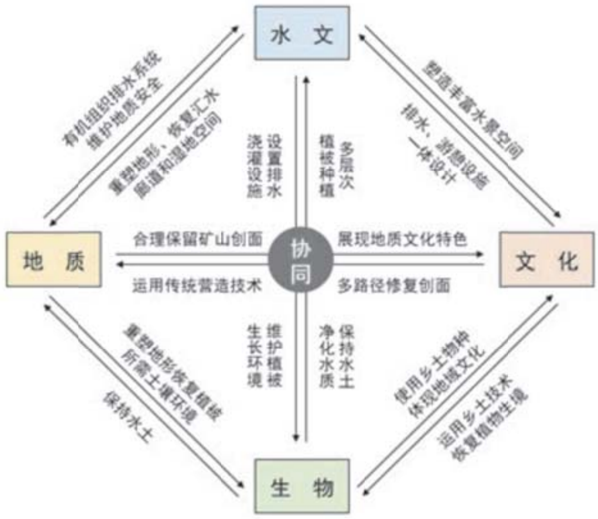


图3　废弃矿山生态修复的技术要点

Figure 3 Technical Points of Ecological Restoration of Abandoned Mines

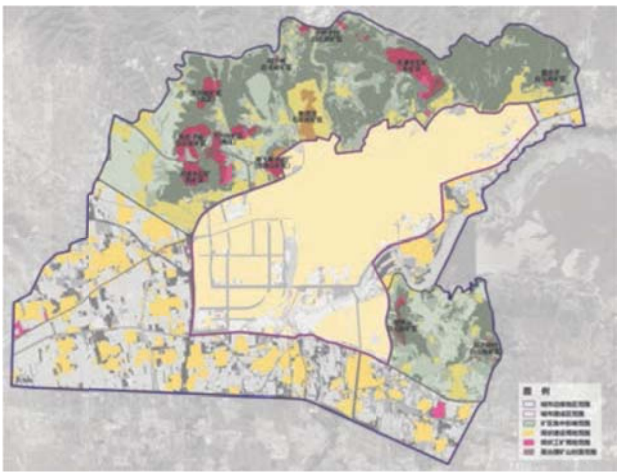


图4　蓟州城市边缘地区废弃矿山分布现状图（© 城市边缘矿山修复课题组）

Figure 4 Status Map of Abandoned Mines in Jizhou Urban Fringe Area

(©Research Group of Mined Land Restoration in Urban Fringe)

文化安全格局是区域人文生态发展的关键。人工文化环境包括文化遗产保护、工业文化节点活化利用和游憩服务体系等，研究选取文化遗产布局作为现状评价指标，文化及服务节点和游憩线路两个指标作为重构评价指标，共同构成区域文化安全格局。

综合分析上述四个方面生态安全格局的影响因子、指标权重及评价标准，最终构建由十个现状评价指标和七个重构评价指标组成的废弃矿山区域生态安全格局评价模型（表1）。

5. 生态安全格局视角下废弃矿山生态修复的过程

基于上述评价模型，在现状及历史资料调查基础上，从单一格局的评价与修复和综合格局的重构与利用两个层次入手，采取如图2所示步骤对废弃矿山及周边区域进行系统性生态修复。

5.1 单一生态格局的评价与修复

针对废弃矿山所在流域单元的各子系统评价指标，开展单一生态格局现状评价，提出各子系统存在的问题及其生态修复的目标。从水文重塑、地形修复、植被恢复和文化复兴四个方面出发，提出各子系统生态修复的策略和关键技术。在维护区域尺度单一系统生态安全的同时，综合考虑给子系统之间的协同作用，形成区域生态安全格局修复的综合方案（图 3），并确定修复后各子系统的单一生态格局。

5.2 综合生态格局的重构与利用

对修复后各子系统的单一生态格局进行叠加分析，综合评价废弃矿山治理后区域的生态敏感性，确定生态安全范围和生态空间架构，重构区域生态安全格局。将区域生态安全格局与现状建设用地相叠加，并与现行生态保护、基本农田、开发边界等管控界线和要求进行比对，在保证建设空间不增加，生态、农业空间不减少的前提下，提出国土空间布局和相关管控界限的优化建议，严格保护生态敏感空间，有机引导城市发展。

结合区域生态安全格局和国土空间布局，确定具体建设方案。一方面，统筹考虑存量工矿用地和农村集体土地的活化利用，提出各矿区适宜的土地再利用模式和详细规划方案。另一方面，将生态基础设施、景观游憩系统与生态格局修复相融合，提出保障区域生态安全的开放空间系统规划方案，为城市提供雨洪管理、休闲游憩、慢行交通、文化展示、环境教育等综合服务。

6. 生态安全格局视角下城市边缘废弃矿山生态修复的技术探索——以天津市蓟州区为例

6.1 蓟州区城市边缘地区废弃矿山区域现状概况

城市边缘地区是指城市建成区周边环绕的，城市物质要素扩散可及的地区[13]。结合蓟州区城市发展的特征，本研究确定的研究范围为规划城市开发边界外 2 km自然流域范围内、城市建成区以外的区域，总面积约 91.5 km^2。

根据 2018 年更新的第二次国土调查数据统计，蓟州区城市边缘现状工矿用地 90 宗，总面积约 4.5 km^2；较集中矿区 11 处，创面总面积约 3.6 km^2 [14]，主要影响范围为北部山前地区和东南部翠屏山地区（图 4）。

6.2 蓟州区城市边缘地区生态安全格局现状评价

运用废弃矿山区域生态安全格局评价模型，从水文、地质、生物、文化四个方面分析蓟州区城市边缘地区生态格局的现状特征及问题（图 5）。

水文安全格局方面，自然水环境现状为山区季节性来水，经七条南北贯穿的山水通廊，汇入城区东南部的于桥水库和州河。矿山开采割断了山区汇水廊道，裸露的岩石降低了土壤含水能力，造成了雨洪灾害的风险。人工水环境规划为山区雨洪沿截洪沟绕城而过，城市雨水沿雨水管网排出。随着城市扩张，规划截洪沟由于技术问题无法实施，城区防洪安全受到严重威胁。

地质安全格局方面，现状地形总体北高南低，五名山、府君山、翠屏山等坡度较大的山体分布在城区北部和东南部，景观资源丰富。但大量矿区高陡创面，对城市底景空间的景观风貌造成较大影响。地质安全方面，地质灾害易发区和地震断裂带集中在北部山前地区，废弃矿山区域存在碎石、崩塌、滑坡等地质灾害隐患。

生物安全格局方面，从现状土地利用看，区域内蓝绿空间约占总用地面积的70％，其中林田水草的比重约为 40:54:5:1，耕地、园地等生产型绿地占主导，生态林地主要分布在坡

度较大的山区。从地表植被覆盖情况看，平原地区植被覆盖率较高，山区受地质条件和矿山开采影响，植被环境较差，生物多样性亟待改善。

文化安全格局方面，现状工业文化遗存主要沿北部山前地区东西向展开的工业铁路专用线分布，其中两处保存较完好的工业建筑集群主要分布在天津市石矿东、西矿区。这些文化遗存展现了当地建材产业发展的历史脉络，是区域文化产业转型发展的核心资源。

6.3 蓟州区废弃矿山生态修复的技术探索

基于上述分析，应对蓟州城市边缘地区防洪安全威胁、地质安全隐患、植被环境破坏和文化资源利用等问题，统筹考虑各单一要素生态格局的修复要点，通过以下四方面关键技术，实现各要素间的协同治理，重构区域生态安全格局。

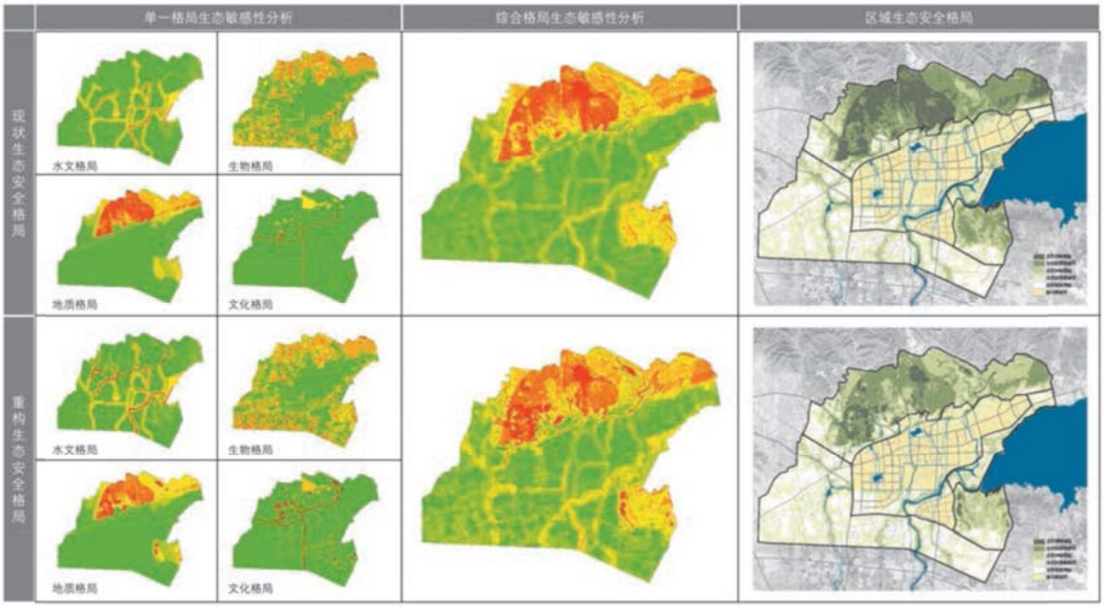


图5 蓟州城市边缘地区生态安全格局评价及重构分析（© 城市边缘矿山修复课题组）
Figure 5 Evaluation and Reconstruction of Ecological Security Pattern in Jizhou Urban Fringe Area (© Research Group of Mined Land Restoration in Urban Fringe)

构建生态功能与景观效果兼具的水文安全格局。在流域层面，系统优化山区雨洪管理网络，合理安排山洪蓄滞空间与排泄通道，降低截洪沟排水压力，并结合矿山治理在城市边缘地区构建多级多塘的生态型截洪体系。在区域层面， 综合考虑地质安全和植被生长需要，通过地形改造和土壤修复，修补被割裂的水文系统，增强含水保水能力，保证山区地质安全。在矿区层面，将矿山治理、景观游憩与灰、绿基础设施建设相结合，营造丰富的水景空间（图6）。

构建生态安全与土地利用并重的地质安全格局。在运用工程化治理技术消除地质灾害隐患，保证地质环境安全的基础上，综合考虑现状地形条件与水文、生物环境修复的需要，确定地形改造方案。同时，充分考虑后期生态建设与空间使用需要，形成适宜植被生长和开发建设的地形条件，实现土地的持续利用。

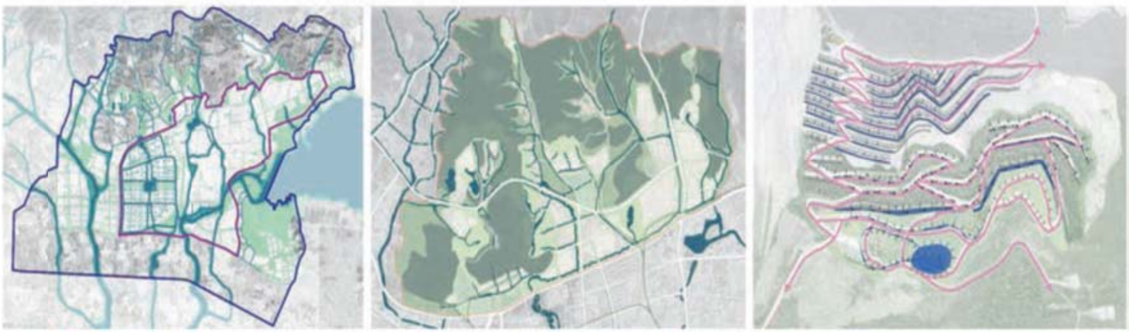
构建自然生态与乡土文化相融的生物安全格局。一方面，通过地形改造和理化技术的应用，恢复适宜植物生长的土壤环境。另一方面，结合地形条件种植多层次植被，形成林田水草复合型生态系统，改善生物多样性。如大兴峪北矿区的治理中，运用旱地梯田的农业技法

建设阶梯平台，植栽松柏、椿类、果木等大小乔木，运用堆山理水的造园手法建设湿地缓冲区，植栽水陆两生地被植物，形成从陆生到水生的多层次植被生境，为不同类型的生物提供栖息环境（图 7）。

构建历史传承与产业转型共赢的文化安全格局。挖掘工矿文化价值，结合特色地形地貌、建筑遗存打造文化景观节点和旅游服务设施。突出地域文化特色，运用乡土景观技术、传统建筑及园林手法，实现人工环境与自然环境、建筑空间与地形改造的协调统一。构建文化产业体系，将游憩系统、文化体验、产业项目相结合，通过存量工矿用地的活化利用，形成特色工矿文化主题产业带，带动区域产业转型与综合发展。

6.4 生态安全格局引导下的蓟州区城市边缘废弃矿山区域国土空间布局优化

针对蓟州区城市边缘地区两处较为集中的废弃矿山区域，结合现状生态安全格局评价结果，应用上述技术开展水文、地质、生物和文化安全单一格局的生态修复。此后，叠加分析各子系统修复后的生态安全格局，综合评价蓟州城市边缘地区的生态敏感性。北部山区由于地质条件、植被覆盖和中上元古界保护区等因素，总体生态敏感性较高，需要重点保护，其山前坡度较缓的区域和部分改造后矿区可进行适当的低强度建设。翠屏山地区受水源地保护制约，其北侧靠近水库区域生态敏感性较高，以生态保护为主，南侧区域为适宜建设区（图 5）。



（a）蓟州城市边缘地区水文格局　（b）蓟州北部矿区水文格局　（c）大兴峪北区矿山修复水文格局

图6 蓟州城市边缘地区各层面水文格局修复路径（© 蓟州矿山治理项目组）

Figure 6yHydrological Pattern Restoration Path in Jizhou Urban Fringe Area(© Project Team of Post-mining Reclamation in Jizhou)

图7 大兴峪北矿区高陡创面地质与生物格局修复路径及效果（© 蓟州矿山治理项目组）
Figure 7 Geological and Biological Pattern Restoration Path and Effect of High and steep cliffin Northern Daxingyu Mining Area (© Project Team of Post-mining Reclamation in Jizhou)

基于区域生态敏感性评价结果，确定各矿区的改造模式与再利用方向。在大兴峪、渔山等较高生态敏感性的矿区治理中，强调生态环境的修复，通过生态保育与公园建设，提升周边适宜建设空间价值，促进区域发展。在翠屏山、飞雁水泥厂等中低生态敏感性的矿区治理中，强调存量工矿用地的综合利用，在维护区域生态安全的同时，发挥土地价值、引导区域转型升级。在老虎顶等生态敏感性混合分布的矿区治理中，采取修复与利用相结合的模式，实现生态效益与社会、经济效益的共赢。

在生态安全格局分析的基础上，综合考虑现状建设用地布局与各类规划管控界限的关系，实现建设用地、开放空间、管控区划在国土空间布局中的统筹优化（图 8）。一方面提出开发边界的调整建议，将原规划中敏感性较高的生态区域及矿山治理复绿的区域从开发边界中扣除，将建设用地指标转移至生态敏感性较低的适宜建设区，结合存量工矿用地和集体土地的再利用重新布局。另一方面将生态空间与生态基础设施、景观游憩系统相结合，形成国土空间布局中的开放空间系统，分别作为生态保护、农业生产和城市绿地进行管理。

7. 结语

从区域生态安全的视角出发，开展废弃矿山生态修复的理论研究与技术实践，强调了生态系统的多元复合性和区域统筹性，凸显了生态系统与城市空间的相互作用。理论研究上，提出了应用废弃矿山生态安全格局评价模型，重构区域生态安全格局、优化国土空间布局的方法。技术实践上，以蓟州区城市边缘地区为例，从水文格局修复、地质环境治理、生物多样性保护和文化游憩系统建设等方面，提出了矿区生态修复的技术要点，并提出了多系统协同治理的技术路径。

应用理论研究和技术探索成果初步实现了蓟州区城市边缘地区生态环境的改善，推进了区域产业转型与社会效益的提升。作为京津冀地区11个矿山地质环境重点治理区之一，以蓟州为例取得的相关研究成果具有一定的典型性，在该地区其余待修复矿山中具备技术可行性，并已在河北省部分地区进行了类似实践推广。开展海河流域源头地区废弃矿山生态修复，并以此为先导重构区域生态安全格局、引导城市有机发展，对于维护山前区域生态安全，推进

京津冀生态协同发展具有重要意义。

后续研究中，可以参照本研究方法对其他自然地理和社会经济条件下的废弃矿山区域生态安全格局评价模型和生态修复路径进行拓展研究；也可以从废弃矿山土地再利用决策和公共政策制定等方面出发，进一步提升矿区生态修复与低效用地转型的水平，实现区域全面可持续发展。

（致谢：感谢“天津市蓟州区矿山地质环境综合治理示范工程”项目组成员褚俊民、李萌、王贤哲、权伟提供的技术和资料支持！）

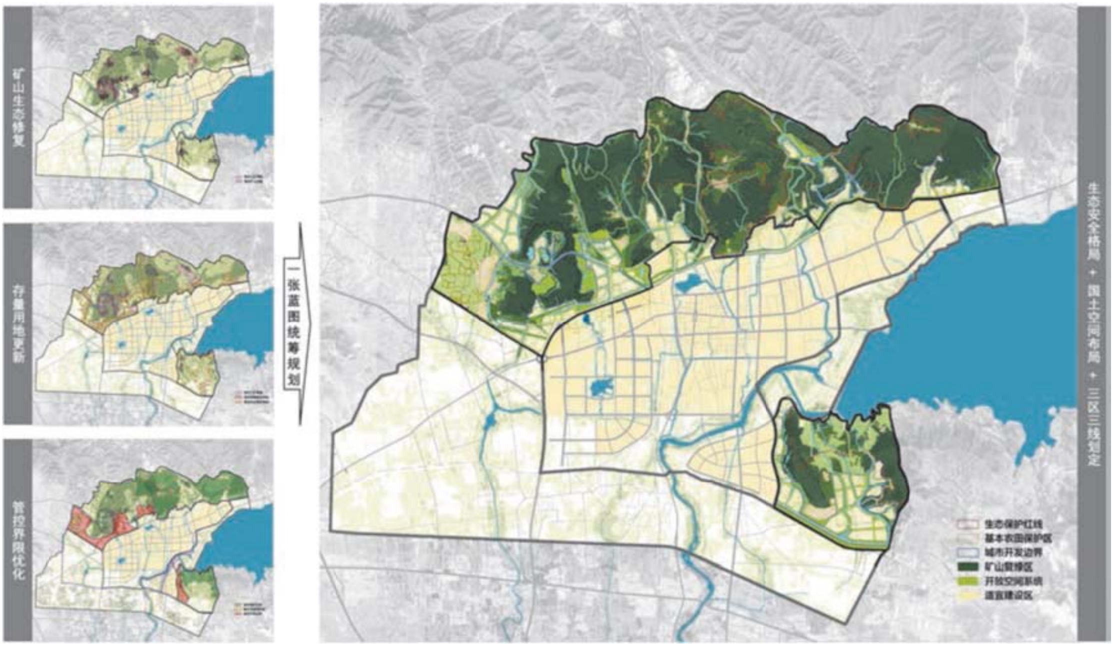


图8 蓟蓟州城市边缘地区国土空间布局优化模式图（© 城市边缘矿山修复课题组）
Figure 8vTerritorial Spatial Pattern Reconstruction Diagram in Jizhou Urban Fringe Area(© Research Group of Mined Land Restoration in Urban Fringe)

1. Research Background

During the period of rapid urbanization, urban construction and economic development depend excessively on the exploitation and utilization of resources. With the transformation of urban development, amounts of mines around the country have been closed down. By 2016, there were 524 key post-mining geological restoration areas in China. The accumulated damaged land in mining exceeded 3.75 million hectare [1]. A large number of abandoned mines not only endanger the ecological environment and the safety of the residents, but also affect the regional ecological security pattern in the surrounding area.

Since the 18th Party Congress put forward the strategy of "ecological civilization construction", the regional ecological co-governance has been highly regarded by governments at all levels. The mountains, rivers, forests, fields, lakes and grasslands in the river basin are a community of life [2]. It is an important means to promote regional ecological coordination to repair ecological environment and reconstruct ecological security pattern. The key to the reconstruction of the headstream ecounit is the comprehensive management of mountain environment, which is led by the ecological restoration of abandoned mines.

At present, the research on ecological restoration of abandoned mines is limited to the problems of geological safety, vegetation restoration, land reclamation and reuse, and the influence on the surrounding area is neglected. The theory of regional ecological security pattern is introduced into the study of ecological restoration of abandoned mines, and the systematic management of hydrology, geology, biology, culture and other factors from the regional perspective is of great significance to the ecological improvement and sustainable utilization of land in post-mining areas.

2. Theory of Ecological Security Pattern and Ecological Restoration of Abandoned Mines

2.1 Evolution and Application of Ecological Security Pattern Theory

In the 20th century, McHaggard's" design with nature "realized the comprehensive evaluation method of land suitability by means of map superposition, which became the rudiment of ecological security pattern theory[3]. At the end of the 20th century, based on the theory of ecological planning and landscape ecology, the theory of landscape urbanism was derived, and ecological landscape was advocated as the basic pattern of urban development[4]. At the beginning of the 21st century, Yu Kongjian put forward the key pattern of supporting natural ecological system, providing ecological services for cities and residents, maintaining the integrity and stability of ecosystem[5].

The theory of ecological security pattern was mainly applied to the analysis of ecological sensitive areas such as nature reserves, and then was gradually introduced into the evaluation of the suitability of land for urban construction, the demarcation of urban development boundaries and the planning of ecosystem. Only Zeng Hui, Zhang Hongjie, etc. (2010), and Wei Congli, Zhang Jianjun, etc. (2017), have studied the path and method of ecological restoration in Wuan mining area from the perspective of regional ecological security pattern [6] [7].

2.2 The Practice and Inadequacy of Ecological Restoration of Abandoned Mines

In the world, the ecological restoration of abandoned mines starts early. Since the 1960s, many countries have carried out ecological restoration and engineering reconstruction of abandoned mines. At the end of the 20th century, Germany and other European countries combined the ecological restoration of industrial and mining land with urban events, which led to the revival of regional culture. Since the 21st century, new technology and new materials have been applied in the project of Eden Project in England, realizing the organic symbiosis between nature and man-made environment. In China, the early practice of ecological restoration of abandoned mines such as Xuzhou and Pingdingshan mainly consists of simple land reclamation. Since 2011, the unification of ecological restoration and landscape reconstruction has been achieved in the construction of Shanghai Chenshan and Hubei Huangshi mine parks.

At present, there are two main problems in ecological restoration of abandoned mines. On the macro-level, the traditional restoration mode focuses on the landscape and ecological effect of the mining area itself. It does not combine the ecological restoration of the mining area with the hydrological environment and ecological pattern, and cannot realize the sustainable improvement of the regional ecological environment. On the micro-level, most of the restoration projects only consider eliminating the hidden danger of geological disasters and simple greening and beautification, the restoration effect has limitations, usually cannot meet the need of long-term comprehensive utilization.

2.3 Key Points of Ecological Restoration in Abandoned Mines from the Perspective of Ecological Security Pattern

Introducing ecological security pattern theory and ecological sensitivity analysis method into abandoned mine ecological restoration can change the original isolated individual restoration mode and realize the restoration and reconstruction of the whole elements of post-mining area and regional ecosystem.

Firstly, it is macroscopical radiative. In determining the land reuse pattern of each mining area, the ecological restoration and transformation requirements of the river basin scale are considered, the open space and construction land are arranged systematically, the ecological security pattern is reconstructed and the territorial spatial pattern is optimized.

Secondly, it is microscopical synthetic. In determining the ecological restoration scheme of each mining area, the requirements and synergetic relations of restoration of various elements in different subsystems, such as hydrology, geology, biology and culture, are considered in order to form a comprehensive ecological restoration technology of engineering, ecology and landscape.

3. The Goal of Ecological Restoration of Abandoned Mines from the Perspective of Ecological Security Pattern

Mining has damaged the stability of natural subsystems such as regional hydrology, geology and biology in different degrees, which leads to the problems such as the destroy of water system, the reduction of rainwater storage capacity, the serious hidden hazards of geological disasters, the poor landscape features, soil erosion, and the destruction of plant habitat. At the same time, industrial mining also left a large number of industrial and mining land and cultural heritage, for the regional revival of valuable cultural resources.

Therefore, the goal of ecological restoration of abandoned mines from the perspective of ecological security pattern is to repair the hydrologic system and enhance the capacity of rainwater and flood management; to reconstruct landform and maintain geological and ecological security; to improve soil environment and restore multi-level plant habitat; to build recreation network and activate mining culture resources. Finally, the systematic restoration of ecology and the sustainable development of the region are realized.

4. Methods of Ecological Restoration of Abandoned Mines from the Perspective of Ecological Security Pattern

Taking Jizhou district of Tianjin as an example, six experts who have been involved in the local work for a long time were invited to study the ecological security pattern and evaluation model of post-mining areas in the special geographical environment of North China Plain and Beijing-Tianjin-Hebei region by means of interview and questionnaire. Firstly, based on the relevant indicators proposed in the previous studies on ecological security pattern and land use suitability [8][9], and considering the special environmental characteristics of abandoned mines and the restoration target[10][11], this paper puts forward a regional ecological security pattern of postmining areas composed of natural ecological subsystems such as hydrology, geology, biology and cultural and humanistic ecological subsystems. Some natural and artificial environmental indicators and evaluation criteria of each indicator are determined, which are respectively used to characterize the current and reconstructed ecological security pattern of post-mining areas. On this basis, by using comprehensive evaluation method and analytic hierarchy process[12], the weight of each sub-system and each factor is determined as it shows in the figure1.

Hydrological security pattern is the foundation of regional ecological security. Natural hydrological environment includes lakes, rivers and other year-round covered surface water, and water catchment corridor, wetland and other seasonal waters.The artificial hydrological environment includes the gray infrastructure such as flood discharge channel, rain and sewage pipe network, and the green infrastructure such as catchment corridor and constructed wetland built in mine restoration. Three indexes, namely surface water area, seasonal water area and gray infrastructure, were selected as current evaluation index and green infrastructure as reconstruction evaluation index to form regional hydrological security pattern.

Geological security pattern is the key point of regional ecological restoration of abandoned mines. Natural geological environment includes landform features such as slope and elevation, and geological safety features such as earthquake disaster area and fault zone, geological disaster prone area, etc. The artificial geological environment includes the geological hazard area and buffer zone left after mine restoration, and the designed special terrain area. Four indexes of natural geological environment were selected as current evaluation indexes, and two indexes of artificial geological environment were used as reconstruction evaluation indexes to form regional geological security pattern.

Biological security pattern is the guarantee of long-term regional ecological stability. The natural biological environment includes plant community and animal community, in which the spatial distribution of animal community can be indirectly analyzed through the distribution, species and growth status of vegetation. The artificial biological environment includes the suitable planting area defined by technical angle, the basic farmland and ecological reserve forest determined by policy angle and so on. In this study, NDVI and green space types were selected as current evaluation indexes, and two indexes of artificial biological environment were used as reconstruction evaluation indexes to form regional biological security pattern.

Cultural security pattern is the key to the development of regional humanistic ecology. The artificial cultural environment includes protection of cultural heritage, activation and utilization of industrial cultural legacy and recreational service system. The distribution of cultural heritage is selected as the evaluation index of current situation, cultural and service facilities and recreational routes are selected as reconstruction evaluation indexes, which together constitute the regional cultural security pattern.

This paper analyzes the indicators, weights and evaluation criteria of ecological security pattern in the four aspects, and finally constructs an evaluation model of regional ecological security pattern in post-mining area (table 1), which is composed of 10 current evaluation indexes and 7 reconstruction evaluation indexes.

5. The Process of Ecological Restoration of Abandoned Mines from the Perspective of Ecological Security Pattern

Based on the above evaluation model, considering the present and historical situation investigation, this paper takes the steps as shown in figure 2 to carry out systematic ecological restoration of abandoned mines and surrounding areas from the two levels of evaluation and restoration of a single ecological security pattern and the reconstruction and utilization of a comprehensive ecological security pattern.

5.1 Evaluation and Restoration of a Single Ecological Security Pattern

In view of the evaluation indexes of each subsystem of the abandoned mines located watershed, the present situation evaluation of single ecological security pattern is carried out, and the existing problems of each subsystem and the target of ecological restoration are put forward. The strategies and key technologies of ecological restoration of subsystems are put forward from four aspects: hydrological reconstruction, topographic restoration, vegetation restoration and cultural revival. While maintaining the ecological security of a single system of regional scale, taking into account the synergy among the sub-systems, the comprehensive scheme of regional ecological security pattern restoration is formed (figure 3), and the single ecological pattern of each sub-system after restoration is determined.

5.2 Reconstruction and Utilization of Comprehensive Ecological Security Pattern

The ecological sensitivity of restored post-mining areas is evaluated comprehensively by overlapping and analyzing single ecological patterns of each sub-system after restoration, in order to determine the ecological security scope and ecological space structure, and to reconstruct the regional ecological security pattern. Then, the regional ecological security pattern is superimposed with the present construction land, and compared with the existing control boundary and requirements of ecological protection, basic farmland, development boundary, etc. On the premise of ensuring the construction space does not increase, the ecological and agricultural space does not reduced, suggestions on optimizing the territorial spatial pattern and related control boundaries are put forward, to protect the ecological sensitive areas strictly and to guide the growth of the city areas organically.

According to the regional ecological security pattern and the territorial spatial pattern, the concrete construction plan will be determined. On the one hand, taking the utilization of stocked industrial and mining land and rural collective land as an overall consideration, suitable land reuse model and detailed plan for each mining area could be proposed. On the other hand, combining ecological infrastructure, landscape recreation system and ecological restoration, an open space system planning scheme to ensure regional ecological security could be put forward to provide comprehensive services such as rainwater management, recreation, slow traffic, cultural display and environmental education for cities.

6. Technical Exploration on Ecological Restoration of Abandoned Mines in Urban Fringe Areas from the Perspective of Ecological Security Pattern: Taking the Jizhou District of Tianjin as an Example

6.1 Present Situation of Post-mining Areas in Jizhou Urban Fringe Area

Urban fringe area refers to the area surrounding the built-up area and where the material elements of the city can be diffused [13]. Based on the characteristics of urban development in Jizhou district, the research scope of this study is about 91.5 square kilometers, which is within two kilometers of the built-up area and the natural watershed, except for the built-up area.

According to the statistics of the second land survey data updated in 2018, there are 90 industrial and mining sites covering an area of about 4.5 square kilometers in Jizhou. The destroyed area is about 3.6 square kilometers [14] in 11 concentrated mining areas, which mainly affects the northern mountain front area and the southeast area of Cui Ping Mountain (figure 4).

6.2 Evaluation of Ecological Security Pattern in Jizhou Urban Fringe Area

The current situation, characteristics and problems of ecological pattern in Jizhou urban fringe area are analyzed from four aspects of hydrology, geology, biology and culture by using the evaluation model of regional ecological security pattern in post mining areas (figure 5).

In terms of the hydrological security pattern, the current situation of natural water environment is seasonal water coming from mountainous area, through seven north-to-south landscape and water catchment corridors; it will converge into Yuqiao Reservoir and Zhouhe River in the southeast of the city. Mining cut off the water catchment corridors in mountainous area, exposed rock reduced the waterbearing capacity of the soil, resulting in the risk of rain and flood disasters. The artificial water environment planning is the mountainous area rain flood along the intercepting ditch around the city and the urban rainwater along the rainwater pipe network. With the expansion of the city, the planning of flood-intercepting ditch cannot be implemented due to technical problems, and the safety of urban flood control is seriously threatened.

In terms of the geological security pattern, the present landform situation is high in the north and low in the south, and the high slope mountains, namely, Wu Ming

Mountain, Fu Jun Mountain and Cui Ping Mountain are distributed in the north and southeast of the city, which are rich in landscape resources. However, a large number of hign and steep cliffs in mining areas located at the background of the city have a great impact on urban landscape. Considering geological safety, the geological disaster prone area and seismic fault zone are concentrated in the northern mountain front area, and there are potential geological hazards such as crushed stone, collapse and landslide in abandoned mine area.

In terms of the biological security patter, the blue-green space in the region accounts for about 70% of the total land use area, among which the proportion of the forest field aquatic grass is about 40:54:5:1, based on the present land use investigation.Among the green spaces, the productive green land such as farm land and garden land is dominant, and the ecological forest land is mainly distributed in the mountainous area with high slope. According to the surface vegetation coverage,the vegetation coverage of plain area is high, affected by geological condition and mining, the vegetation environment in the mountainous area is poor, and the biodiversity needs to be improved urgently.

In terms of the cultural security pattern, the present industrial cultural heritages are mainly distributed along the east-west direction industrial railway lines located at the front of the northern mountain area, two of which are well-preserved industrial building clusters mainly distributed in the east and west stone mines of the Tianjin Construction Material Group. These cultural heritages show the historical context of the development of local construction materials industry and are the core resources of regional cultural industry transformation and development.

6.3 Technical Exploration on Ecological Restoration of Abandoned Mines in Jizhou District

Based on the above analysis, problems such as the threat of flood control safety, the hidden danger of geological safety, the destruction of vegetation environment and the utilization of cultural resources should be deal with in Jizhou urban fringe area. Considering the key points of ecological security pattern restoration of each single factor as a whole, applying the following four key technical points, the coordinated management among different subsystems and indicators could be realized to reconstruct the regional ecological security pattern.

Construct a hydrological security pattern with ecological function and landscape effect. At the watershed level, the rain flood management network of mountainous area is optimized, the storage space and drainage channel of mountain flood are reasonably arranged, the drainage pressure of the flood-blocking ditch is reduced, and the ecological flood-blocking system with multi-stage and multipond is constructed in the urban fringe area in combination with mine restoration.

At the regional level, the geological safety and the vegetation growth need are comprehensively considered, and the fractured hydrological system is repaired through topographic reformation and soil restoration, so that the water-containing and water-retaining capacity is enhanced, and the geological safety of mountain areas is ensured. At the mine level, the mine restoration is combined with landscape recreation and the construction of grey and green infrastructure to create abundant waterscape space (figure 6).

Construct a geological security pattern with equal emphasis on ecological security and land use. On the basis of using engineering restoration technology to eliminate the hidden danger of geological disasters and ensure the safety of geological environment, the topographic reformation plan is determined by considering the current topographic conditions and the need of hydrological and biological environmental restoration. At the same time, taking full account of the need of ecological recovery and land use in the long term, the terrain conditions suitable for vegetation growth and development are reformed to realize the sustainable use of land resources.

Construct a biological security pattern of coordinated natural ecology and local culture. On the one hand, the soil environment suitable for plant growth can be restored by topographic reformation and the application of physical and chemical technology. On the other hand, multi-level vegetation was planted in combination with topographic conditions to form a compound ecosystem of forest, farmland, water space and grass to improve biodiversity. For example, in the treatment of Northern Daxingyu mining area, the agricultural techniques of terraced fields are used to build platforms, and different types of trees, such as pine, cypress, stump and fruit trees are planted. Meanwhile, the traditional gardening method of manmade landscape is introduce to build wetland buffer zone, and amphibious ground cover plants are planted to form a multi-level vegetation habitat from land to water, providing habitat for different types of living organisms (figure 7).

Construct a cultural security pattern with a win-win situation of historical inheritance and industrial transformation. Explore industrial and mining cultural value, combined with the features of mining landforms, architectural heritage to create cultural landscape landmarks and tourism service facilities. Highlighting the regional cultural characteristics, the local landscape, traditional architectural and gardening techniques are used to realize the harmony of artificial and natural environment, and the coordination of building space and landform reconstruction. Combining recreational system, cultural experience and industrial project, a cultural industry system is developed, through the activation and utilization of stocked industrial and mining land, forming characteristic industrial and mining culture theme industrial belt, promoting regional industrial transformation and comprehensive development.

6.4 Optimization of Territorial Spatial Pattern of Post-mining Areas in Jizhou Urban Fringe Area under the Guidance of Ecological Security Pattern

According to the evaluation results of the present ecological security pattern in the two main post-mining areas of Jizhou Urban Fringe Area, applying the above technologies, the single pattern of hydrological, geological, biological and cultural ecological security is restored. After that, the ecological security pattern of each sub-system is overlapped and analyzed to evaluate the ecological sensitivity of Jizhou urban fringe area synthetically. Because of geological conditions, vegetation cover and protection area of Middle and Upper Proterozoic, the overall ecological sensitivity is higher in the northern mountainous area, so special protection is needed. The area of Cui Ping Mountain is restricted by the protection of water source area, and its north side which is close to the reservoir area is with high ecological sensitivity and should be dominated by ecological protection, while the south side is suitable for construction (figure 5).

Based on the result of regional ecological sensitivity evaluation, the transformation mode and reutilization direction of each mining area are determined. In the redevelopment of mining areas with high ecological sensitivity, such as Daxingyu and Yushan, the restoration of ecological environment is emphasized, and the land value of surrounding area is enhanced through ecological conservation and park construction, so as to promote regional development. In the redevelopment of mining areas with middle and low ecological sensitivity, such as Cui Ping Mountain and Feiyan Cement Plant, the comprehensive utilization of the stocked industrial and mining land is emphasized, and the land value is brought into play while maintaining the regional ecological security, leading the transformation and upgrading of the regional industrial system. In the redevelopment of mining areas with mixed ecological sensitivity, such as the Laohuding Mine, the combination of restoration and utilization is adopted to realize the win-win situation between ecological benefit and social and economic benefit.

On the basis of ecological security pattern analysis, the relationship between the layout of present construction land and various planning control boundaries is considered comprehensively to realize the overall optimization of construction land,open space and control boundaries in the territorial spatial plan (figure 8).

On the one hand, some suggestions are put forward to adjust the development boundary, which are deducted the development boundary from the eco-area with high sensitivity and the area with ecological restoration of mines, and the construction land is relocated into the suitable construction area with low ecological sensitivity, following the redistribution of the stocked industrial and mining land and collective land.

On the other hand, it combines ecological space with ecological infrastructure and landscape recreation system to form an open space system in the territorial spatial plan, which is managed as ecological protection, agricultural production and urban green space respectively.

7. Conclusions

From the perspective of regional ecological security, the theoretical research and technical practice of ecological restoration in abandoned mines are carried out, which emphasizes the multi-complex and regional co-ordination of ecosystem, and highlights the interaction between ecosystem and urban space. In theory, this paper puts forward the method of applying the ecological security pattern evaluation model of post-mining areas, to reconstruct the regional ecological security pattern and optimize the territorial spatial pattern. In practice, taking Jizhou urban fringe area as an example, from the aspects of hydrological pattern restoration, geological environment reformation, biodiversity conservation and cultural recreation system construction, this paper puts forward the technical points of ecological restoration of abandoned mines, and puts forward the technical path of multi-system coordinated management.

By applying the results of theoretical research and technical exploration, the improvement of ecological environment and the promotion of regional industrial transformation and social benefit are realized in Jizhou urban fringe area. As one of the 11 key post-mining geological restoration areas in Beijing-Tianjin-Hebei area, the related research results obtained by taking Jizhou as an example are typical, and have technical feasibility in other mines to be repaired in this area, and have been introduced in the practices of some similar areas in Hebei Province. To carry out the ecological restoration of abandoned mines in the headstream area of Haihe Basin and to reconstruct the regional ecological security pattern and guide the organic development of cities is of great significance to the maintenance of ecological security in the mountain front area and the promotion of the coordinated ecological development in Beijing, Tianjin and Hebei provinces.

In the follow-up research, the ecological security pattern evaluation model and ecological restoration path of post-mining areas and abandoned mines under other physical geography and social economic conditions can be expanded and studied according to the research method. It is also possible to further improve the level of ecological restoration and low-utility land transformation in post-mining areas from the aspects of land use decision-making and public policy, so as to realize regional comprehensive sustainable development.

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